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OPTIMAL ENVIRONMENTAL POLICY DESIGN IN THE PRESENCE OF UNCERTAINTY AND TECHNOLOGY SPILLOVERS

by

Patrick Himmes

and

Christoph Weber

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by P. Himmes and C. Weber

Abstract

The stylized model presented in this paper extends the approach developed by Fischer and Newell (2008) by analysing the optimal policy design in a context with more than one externality while taking explicitly into account uncertainty surrounding future emission damage costs.

In the presence of massive uncertainties and technology spillovers, well-designed support mechanisms for renewables are found to play a major role, notably as a means for compensating for technology spillovers, yet also for reducing the investors' risks. However, the design of these support mechanisms needs to be target-aimed and well-focused. Besides uncertainty on the state of the world concerning actual marginal emission damage, we consider the technological progress through R&D as well as learning-by-doing. A portfolio of three policy instruments is then needed to cope with the existing externalities and optimal instrument choice is shown to be dependent on risk aversion of society as a whole as well as of entrepreneurs.

To illustrate the role of uncertainty for the practical choice of policy instruments, an empirical application is considered. The application is calibrated to recent global data from IEA and thus allows identifying the main drivers for the optimal policy mix. In addition to assumptions on technology costs and uncertainty of emission damage cost, the importance of technology spillover clearly plays a key role. Yet under some plausible parameter settings, direct subsidies to production are found to be of lower importance than very substantial R&D supports.

Keywords:

Externality, technology, learning, uncertainty, climate change, spillover, renewable energy, policy

JEL-Classification:

O38, Q21, Q28, Q48

P. HIMMES
Chair for Management Sciences and Energy Economics,
University of Duisburg-Essen (Campus Essen)
Universitätsstr. 11, 45117 Essen
+49 - 0201 / 183-7306
www.ewl.wiwi.uni-due.de
patrick.himmes@uni-due.de

C. WEBER
Chair for Management Sciences and Energy Economics,
University of Duisburg-Essen (Campus Essen)
Universitätsstr. 11, 45117 Essen
+49 - 0201 / 183-2966
www.ewl.wiwi.uni-due.de
christoph.weber@uni-due.de

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List of Symbols

B	*environmental benefits*
C	*fossil-fuelled generation production costs*
CS	*consumer surplus*
D	*demand*
E	*total emissions*
G	*renewable generation production costs*
h	*generated knowledge*
H	*total cumulative knowledge from R&D*
i	*technology index*
K	*knowledge stock*
N	*number of generators*
n	*number of years*
P	*price*
q	*renewable technology (output)*
Q	*total learning-by-doing*
R	*research expenditures*
s	*renewable generation subsidy*
S	*utility (firm)*
t	*period*
T	*weighted profit*
U	*utility (welfare)*
V	*government revenues*
x	*coal-fired baseload technology (output)*
y	*marginal gas-powered technology (output)*
δ	*discount rate*
θ	*tax on fossil-fuelled generation*
μ	*technology based emissions*
ξ	*uncertainty*
π	*profit*
ρ	*spillover rate*
σ	*R&D subsidy*
τ	*emissions price*

1 Introduction

Despite intense research and policy efforts, still considerable uncertainties surround climate change, both on the actual strength and impacts and on the costs of any bundle of recipes against it. Standard environmental economics suggests two alternative first-best solutions in this situation: Either install a global cap-and-trade regime for greenhouse gas emissions or globally implement a uniform tax on these emissions. In both cases, the emission cap respectively the tax rate would have to be chosen as to realize the optimal emission level, where marginal damage costs equal marginal mitigation costs (cf. e.g. Baumol and Oates, 1998).

Although the EU emission trading system may be seen as a first step towards a practical implementation of these theoretical insights, current policy practice frequently follows other paths for supporting low carbon technologies. Both in the US and in the EU, states notably use specific programs for promoting renewable energies[1]. In Europe systems of feed-in tariffs are more often used (e.g. Germany), whereas in the US frequently renewable portfolio standards are implemented.

In this paper, the benefits of specific policies beside a general tax or a cap-and-trade are investigated taking especially into account the uncertainty surrounding future emission damage costs. Thereby the focus is on the implications of technology learning and the associated externalities. Following Jaffe et al. (2005), the presence of more than one market failure requires a single policy for every failure (cf. also Tinbergen 1952). Therefore, the presence of knowledge spillovers besides an emissions externality requires multiple instruments to optimally adjust for the externalities (cf. e.g. also Butler, Neuhoff 2008).

Baker and Shittu (2008) give an overview on different papers dealing with uncertainty and endogenous technical change, but all of these do not cover optimal policy design but optimal investments in R&D or learning. Optimal environmental and technology policies are treated in Bläsi and Requate (2007) as well as in Fischer and Newell (2008) and Lehmann (2009). The former consider two types of electricity generators, emitting fossil fuel utilities and a non-emitting renewable sector based on wind energy. Furthermore, they account for the vertical structure of this latter sector by taking into account the wind-turbine producers profiting from learning-by-doing. As well as Bläsi and Requate (2007), Fischer and Newell (2008) and Lehmann (2009) consider the optimal policy instruments, yet they investigate a two-sector model consisting of a renewables sector and a fossil-fuel sector without taking into account the vertical structure. Lehmann extends and focuses the model of Fischer and Newell on Germany including an efficiency effect

[1] But also energy efficiency improvements in buildings and in manufacturing are often subsidized.

and distortions due to add-on payments funding a feed-in tariff. However, all papers do not take into account the impact of uncertainty on future emission damages on the optimal policy.

The stylized model presented in this paper extends the approach developed by Fischer and Newell (2008) by analysing the optimal policy design in a context with more than one externality while taking explicitly into account uncertainty surrounding future emission damage costs. Uncertainty in the context of the optimal choice of climate change policy instruments has also been taken into account by Adar and Griffin (1976) who compare different pollution control instruments with the marginal damage function or the marginal control costs being uncertain. Pizer (1999) shows the importance of including uncertainty in policy design models, even if an integrated climate-economy model is used to examine different policies designs. It is shown that excluding uncertainty leads to reduced expected marginal benefits and therewith to policy recommendations which are not stringent enough. In this paper, we show that the theoretical results established by Fischer and Newell (2008) generally carry through to the case with uncertainty[2]. I.e., if knowledge is accumulated both through R&D and learning-by-doing, then three policy instruments are needed to correct for technology spillovers and emission externalities: an emission tax or cap, an R&D subsidy and a production subsidy. However, in the presence of insolvency costs and the corresponding risk aversion of companies, the R&D subsidy has to increase above the level required under certainty. The same holds for the production subsidy. Moreover it is shown that innovating firms will not be able to recover their costs even in the absence of technology spillover, if there is perfect competition and no R&D subsidy. Besides the theoretical focus on uncertainty, optimal policy instruments are analysed on a global scale. The model brings together two perspectives: a pure social planning point-of-view on the one hand that indicates the optimal societal strategy to cope with uncertainty and on the other hand, a market equilibrium viewpoint to determine the optimal policies to reach the societal targets and to assess the effects on the firms' profits.

The paper is organised as follows: Section two introduces the model with uncertainty before the conditions for a social optimum are discussed in section three. In the next section, optimal policy instruments are investigated and the market equilibrium is examined. In section five, the model is applied to the case of world-wide emission abatement until 2050 and the paper concludes in section six.

[2] Similar results have been established earlier (cf. e.g. Schöb 1995) for first-best environmental policy instruments in the standard textbook setting without knowledge spillover.

2 Model with uncertainty

Following Fischer and Newell (2008), the model encompasses two periods representing each a specific number of years $n^{(1)}$ and $n^{(2)}$. Production and consumption as well as emissions occur in both periods, investment in knowledge by contrast only in the first. Discounting between both periods at a specific factor δ is included, but not within each period.

Two subsectors, a fossil-fuel fired and CO_2-emitting electricity generating sector, denoted with superscript *F,* and a nonemitting renewable energy sector, denoted with superscript *R,* exist in the model. Both take prices as given in each period. The fossil-fuel subsector includes a CO_2 intensive technology *x*, e.g. coal-fired power generation, and a less emitting technology *y*, such as combined cycle gas plants.

With an annual output of fossil-fuelled electricity production $f^{(t)}=x^{(t)}+y^{(t)}$ in period *t*, the total emissions *E* with technologies *i* and fixed emissions μ_i for each technology are:

$$E^{(t)} = \mu_x x^{(t)} + \mu_y y^{(t)} \tag{1}$$

Production costs C_i of each technology are assumed to be increasing in output and strictly convex.

The total output of the renewables sector consisting of *N* different generators in a specific period is $q^t$and the costs of production are $G^{(t)}(K^{(t)}, q^{(t)})$. The knowledge stock $K^{(t)}(H^{(t)}, Q^{(t)})$ is thereby a function of the total cumulative knowledge from R&D $H^{(t)}$, increasing in proportion to the knowledge generated in each period h_1 (i.e. $H_2=H_1+n^{(1)}h_1$) and of the cumulative production $Q^{(t)}$ inducing learning-by-doing. The latter also increases with total output during period 1, i.e. $Q_2=Q_1+n^{(1)}q_1$. Research expenditures $R(h^{(t)})$ are increasing and convex in the amount of new R&D knowledge generated in one year. The factor ρ indicates the degree of appropriability of the R&D benefits by the firm incurring the R&D expenses. Then 1-ρ is the spillover rate. (cf. Fischer and Newell 2008).

In the equilibrium, total consumers' electricity demand *D(P)* must equal total supply, consisting of the fossil-fuel and the renewable energy sectors' output where $P^{(t)}$ denotes the price of electricity:

$$D\left(P^{(t)}\right) = x^{(t)} + y^{(t)} + q^{(t)} \tag{2}$$

In the next subsections, state dependency will be included for all variables that depend on the revealed marginal damage costs for CO_2, i.e. namely the variables at stage 2. Subsequently the objective functions for the different economic agents of the fossil-fuel generators.

2.1 Fossil-fuel sector

The opportunities for a reduction of the greenhouse gas emissions in the fossil-fuel sector rely largely on fuel switching. Let $\tau^{(t)}$ be the price of emissions and $\theta^{(t)}$ be the tax on fossil-fuel generation at time *t.* Depending on state ξ, the profits of a representative emitting firm are:

$$\begin{aligned}\pi^F = n^{(1)}\big[\big(P^{(1)} - \theta_{(1)}\big)\big(x^{(1)} + y^{(1)}\big) - C_x\big(x^{(1)}\big) - C_y\big(y^{(1)}\big) - \tau^{(1)}\big(\mu_x x^{(1)} \\ + \mu_y y^{(1)}\big)\big] \\ + \delta n^{(2)}\big[\big(P^{(2)}(\xi) - \theta^{(2)}(\xi)\big)\big(x^{(2)}(\xi) - y^{(2)}(\xi)\big) - C_x\big(x^{(2)}(\xi)\big) \\ - C_y\big(y^{(2)}(\xi)\big) - \tau^{(2)}\big(\mu_x x^{(2)}(\xi) + \mu_y y^{(2)}(\xi)\big)\big]\end{aligned} \tag{3}$$

With regard to output from each fuel source, the firm maximizes the profits, resulting in the following first order conditions:

$$\frac{\partial \pi^F}{\partial x^{(1)}}=0: \qquad P^{(1)} = \theta^{(1)} + C_x'\big(x^{(1)}\big) + \tau^{(1)}\mu_x \tag{4}$$

$$\frac{\partial \pi^F}{\partial x^{(2)}(\xi)}=0: \qquad P^{(2)}(\xi) = \theta^{(2)}(\xi) + C_x'\big(x^{(2)}(\xi)\big) + \tau^{(2)}\mu_x \tag{5}$$

$$\frac{\partial \pi^F}{\partial y^{(1)}}=0: \qquad P^{(1)} = \theta^{(1)} + C_y'\big(y^{(1)}\big) + \tau^{(1)}\mu_y \tag{6}$$

$$\frac{\partial \pi^F}{\partial y^{(2)}(\xi)}=0: \qquad P^{(2)}(\xi) = \theta^{(2)}(\xi) + C_y'(y^{(2)}(\xi)) + \tau^{(2)}(\xi)\mu_y \tag{7}$$

All together, these equations show that coal generation is used in each period until its marginal costs equal those of gas.

2.2 Renewables sector

Under uncertainty, the profits of a representative renewable electricity generator including a subsidy s for renewable energy production and an R&D subsidy σ are:

$$\pi^R = n^{(1)}\left[\left(P^{(1)} + s^{(1)}\right)\left(q^{(1)}\right) - G\left(K^{(1)}, q^{(1)}\right) - (1-\sigma)R\left(h^{(1)}\right)\right] \\ + \delta n^{(2)}\left[\left(P^{(2)}(\xi) + s^{(2)}(\xi)\right)\left(q^{(2)}(\xi)\right) - G\left(K^{(2)}(\xi), q^{(2)}(\xi)\right)\right] \tag{8}$$

Where

$$K^{(2)}(\xi) = K(H^{(2)}(\xi); Q^{(2)}(\xi))$$

Taking the degree of R&D-investment appropriability ρ into account, the firm maximises the profits with regard to output and R&D investments, resulting in the following first order conditions:

$$\frac{\partial \pi^R}{\partial q^{(1)}}=0: \\ G_q\left(K^{(1)}, q^{(1)}\right) = \\ n^{(1)}(P^{(1)} + s^{(1)} - \delta\rho n^{(2)} \int G_K\left(K^{(2)}(\xi), q^{(2)}(\xi)\right) n^{(1)} K_Q(H^{(2)}(\xi), Q^{(2)}(\xi)) d\,\xi \tag{9}$$

$$\frac{\partial \pi^R}{\partial q^{(2)}(\xi)}=0: \quad G_q\left(K^{(2)}(\xi), q^{(2)}(\xi)\right) = (P^{(2)}(\xi) + s^{(2)}(\xi))q^{(2)}(\xi) \tag{10}$$

$$\frac{\partial \pi^R}{\partial h^{(1)}}=0: \quad R_h\left(h^{(1)}\right) = -\delta \frac{\rho}{(1-\sigma)} n^{(2)} G_K\left(K^{(2)}(\xi), q^{(2)}(\xi)\right) K_H(H^{(2)}(\xi), Q^{(2)}(\xi)) \tag{11}$$

Equation (9) shows that renewable energy is produced until its marginal production costs equal the value of all received payments, including besides the market price and the subsidies also the decreased production costs in the second period, as far as it is appropriable. As no learning is included in period 2, no related term can be found in eq. (10). As shown in eq. (11), the firm invests in R&D until the related discounted returns equal the marginal investment costs for research.

2.3 Household sector

For households it does not matter whether electricity is generated by renewables or fossil-fuel generators, i.e. both are considered as perfect substitutes. With $D(\tilde{P})$ representing the households' total electricity demand, consumer surplus is

$$CS = n^{(1)} \int_{P^{(1)}}^{+\infty} D(\tilde{P}) d\tilde{P} + \delta n^{(2)} \int_{P^{(2)}}^{+\infty} D(\tilde{P}) d\tilde{P} \tag{12}$$

3 Welfare optimum under uncertainty

In this section, the societal optimum under uncertainty is formally derived using the aforementioned sectoral profit functions.

3.1 Welfare under uncertainty

Total welfare is a function of the sum of the producer and consumer rents, to which environmental benefits and governmental revenues/spending have to be added. Given the wide-spread risk aversion among individuals and in entire societies, welfare is set to be a nondecreasing concave utility function U of the aforementioned sum. Moreover welfare is dependent on the state of the world ξ and thus an integration over all possible states of the worlds will deliver the expected welfare to be maximised.

$$W = \int U(B + CS + \pi + V)d\xi \tag{13}$$

The total profit π thereby encompasses the individual profits from both the emitting and the nonemitting sectors representative firm ($\pi = \pi^F + \pi^R$).

3.2 Government revenues

As we use a partial model, the government revenues or spending V, influenced by the implemented policies, have to be considered when computing total welfare. Thereby we assume implicitly in line with Fischer and Newell (2008) that any revenues raised are returned as lump-sum transfers.

$$\begin{aligned} V = n^{(1)}\big(\theta^{(1)} f^{(1)} + \tau^{(1)}\big(\mu_x x^{(1)} + \mu_y y^{(1)}\big) - s^{(1)} q^{(1)} - \sigma R\big(h^{(1)}\big) \\ + \delta n^{(2)}\big(\theta^{(2)}(\xi) f^{(2)}(\xi) + \tau^{(2)}\big(\mu_x x^{(2)}(\xi) + \mu_y y^{(2)}(\xi)\big) \\ - s^{(2)}(\xi) q^{(2)}\big)(\xi) \end{aligned} \tag{14}$$

3.3 Environmental benefits

Climate change mitigation results in environmental benefits B which are a function of the total emissions and can be denoted as follows.

$$\begin{aligned} B &= B\big(n^{(1)}E^{(1)} + n^{(2)}E^{(2)}, \xi\big) \\ &= B\big(n^{(1)}\big(\mu_x x^{(1)} + \mu_y y^{(1)}\big) + n^{(2)}\big(\mu_x x^{(2)}(\xi) + \mu_y y^{(2)}(\xi)\big), \xi\big) \end{aligned} \tag{15}$$

3.4 Conditions for welfare optimum

Maximising the total welfare W(eq. (13)) yields the following first order conditions:

$$\frac{\partial W}{\partial x^{(1)}} = 0: P^{(1)} - C_x'(x^{(1)}) = \frac{\mu_x \int U' \cdot B_E \, d\xi}{\int U' \, d\xi} \tag{16}$$

$$\frac{\partial W}{\partial x^{(2)}} = 0: U' \cdot \left(B_E \, n^{(2)}\mu_x + n^{(2)}\left(P^{(2)} - C_x'(x^{(2)})\right)\right) = 0 \tag{17}$$

$$\frac{\partial W}{\partial q^{(1)}} = 0: \; P^{(1)} - G_q\left(K^{(1)}, q^{(1)}\right) = \delta n^{(2)} \frac{\int U' \cdot G_K\left(K^{(2)}, q^{(2)}\right) d\xi}{\int U' \, d\xi} \cdot K_Q(H^{(2)}, Q^{(2)}) \tag{18}$$

$$\frac{\partial W}{\partial h^{(1)}} = 0: R' = \delta n^{(2)} \frac{-\int U' \cdot G_K\left(K^{(2)}, q^{(2)}\right) d\xi}{\int U' \, d\xi} K_H\left(H^{(2)}, Q^{(2)}\right) \tag{19}$$

$$\frac{\partial W}{\partial P^{(1)}} = 0: n^{(1)} \left(x^{(1)} + y^{(1)} + q^{(1)} - D\left(P^{(1)}\right)\right) \int U' \cdot d\xi = 0 \tag{20}$$

$$\frac{\partial W}{\partial P^{(2)}} = 0: \; \Rightarrow x^{(2)} + y^{(2)} + q^{(2)} - D\left(P^{(2)}\right) = 0 \tag{21}$$

As the welfare optimum in the planner perspective is independent of the tax rates resp. production and R&D subsidies, the corresponding terms vanish in the total welfare and the first-order conditions are not shown here[3]. If U'>0, then eq. (20) leads to an equilibrium of demand and supply in period 1 as does eq. (21) for period 2. This is in line with the market equilibrium postulated in equation (2).

4 Market equilibrium and optimal incentives

4.1 Fossil fuel sector

Under uncertainty, risk aversion implies that the utility of the representative firm's profits is a nondecreasing concave function again to be integrated over all states of the world. This results in the weighted profit T_F:

$$T_F = \int S_F(\pi_F) d\xi \tag{22}$$

[3] Cf. **Appendix A: Further welfare FOC's**

Maximizing these profits yields the following first order conditions:

$$\frac{\partial T_F}{\partial x^{(1)}} = 0:\ n^{(1)} \cdot \left(P^{(1)} - \mu_x \tau^{(1)} - C_x'(x^{(1)})\right) \cdot \int S_F{}' d\xi = 0 \tag{23}$$

$$\frac{\partial T_F}{\partial x^{(2)}} = 0: \delta n^{(2)} \cdot S_F{}' \cdot \left(P^{(2)} - \mu_x \tau^{(2)} - C_x'(x^{(2)})\right) = 0 \tag{24}$$

From eq. (24), the following condition linking prices and taxes may be derived:

$$P^{(2)} - C_x'\left(x^{(2)}\right) = \mu_x \tau^{(2)} \tag{25}$$

By comparing equations (25) and (17), one may easily see that consistent incentives are given if the emission tax equals the marginal change in the environmental benefits:

$$\tau^{(2)} = -B_E \tag{26}$$

Hence as in Fischer and Newell (2008), damages caused by emissions are internalised by setting the emission price in period 2 equal to the marginal damage.

Under uncertainty, the optimal policy for period 1 is somewhat more complicated. Yet, combining eq. (16) and (23) allows identifying the consistent incentives as:

$$\tau^{(1)} = -\frac{\int U' \cdot B_E d\xi}{\int U' d\xi} \tag{27}$$

Hence the optimal tax rate is equal to a weighted average of the marginal damages $-B_E$ under different states of the world ξ, with the corresponding marginal welfare U' used as weighting factor.

Analogously to eq. (23)-(27) for technology x, similar relationships may be established for technology y.

4.2 Renewables sector

For the renewable energy sector, the weighted profit T_R with no renewable generation subsidy ($s^{(2)} = 0$) in period 2 is given by eq. (28):

$$T_R = \int S_R(\pi_R) d\xi \tag{28}$$

From derivatives of the renewable sectors profit function the following conditions may be derived for the first period:

$$\frac{\partial T_R}{\partial q^{(1)}} = 0{:}\, P^{(1)} + s^{(1)} - G_q\big(K^{(2)}, q^{(1)}\big) = \delta n^{(2)} \rho \frac{\int S_R' G_K(K^{(2)}, q^{(2)} d\xi}{\int S_R' d\xi} K_Q(H^{(2)}, Q^{(2)}) \tag{29}$$

$$\frac{\partial T_R}{\partial h^{(1)}} = 0{:}\, (1-\sigma) R' = \delta n^{(2)} \rho \frac{-\int S_R' G_K(K^{(2)}, q^{(2)} d\xi}{\int S_R'\, d\xi} K_H(H^{(2)}, Q^{(2)}) \tag{30}$$

$$\frac{\partial T_R}{\partial q^{(2)}} = 0{:}\, \delta n^{(2)} \cdot {S_R}' \cdot \big(P^{(2)} + s^{(2)} - G_q\ (K^{(2)}, Q^{(2)})\big) = 0 \tag{31}$$

Combining equations (30) and (19), the optimal R&D subsidy σ is given through:

$$\sigma = 1 - \rho \cdot \frac{\frac{\int {S_R}' G_K\left(K^{(2)}, q^{(2)}\right) d\xi}{\int {S_R}' d\xi}}{\frac{\int U' G_K\left(K^{(2)}, q^{(2)}\right) d\xi}{\int U' d\xi}} \tag{32}$$

The share of subsidy is hence clearly decreasing with an increasing degree of appropriation ρ for knowledge. The ratio on the right hand side is a coefficient of two weighted sums of marginal cost reductions through knowledge accumulation. In the denominator, the marginal welfare is used as weights, whereas in the numerator the marginal utility of the firm is used as weight. If the firms are more risk averse (e.g. because they are small) than the society as a whole, then this ratio is strictly smaller than 1. In that case an R&D subsidy is justified even if knowledge is fully appropriable (i.e. $\rho = 1$). The optimal subsidy rate yet turns out to be independent of K_H, i.e. the marginal benefits of R&D expenditure in terms of knowledge accumulation.

Making use of this result, the optimal production subsidy may be obtained by combining eqs. (31), (29) and (18).

$$s^{(1)} = \sigma \cdot \frac{-\int U' G_K(K^{(2)}, q^{(2)}) d\xi}{\int U' d\xi} K_Q(H^{(2)}, Q^{(2)}) \tag{33}$$

The optimal production subsidy then corresponds to the marginal benefits of learning-by-doing, weighted by the marginal utility in the different states of the world and multiplied by the previously determined optimal subsidy share.

5 Empirical application

To illustrate the role of uncertainty for the choice of policy instruments, a highly stylized application is considered. The functional specifications are mostly analogous to those chosen by Fischer and Newell (2008). The application is calibrated to recent global data from IEA (2010) and thus allows identifying the main drivers for the optimal policy mix.

We consider coal and gas power stations to be the conventional technologies x and y and in line with specify quadratic cost functions C_x and C_y respectively:

$$C_x(x) = c_{x0} + c_{x1}x + \tfrac{1}{2}c_{x2}x^2 \quad (34)$$

$$C_y(y) = c_{y0} + c_{y1}y + \tfrac{1}{2}c_{y2}y^2 \quad (35)$$

This implies linear supply functions as shown in Figure 1 for the first period. With the parameter values given in Table 1, coal has the lowest marginal generation costs for any production quantity when excluding climate damage costs, gas can compete with coal only at low generation levels.

For renewables (technology q) also a quadratic cost function G is specified, yet with costs being inversely proportional to the knowledge capital K:

$$G(K, q) = \frac{(g_0 + g_1 q + \frac{1}{2}g_2 q^2)}{K} \quad (36)$$

The parameter values are fixed as indicated in Table 1, so renewables are non-competitive with neither learning nor climate damage costs, as illustrated in Figure 1. Both cumulative R&D expenditures of previous periods H_t and cumulative previous production Q_t contribute through a power function to knowledge K_t:

$$K_t = \left(\frac{H_t}{H_1}\right)^{k_1} \left(\frac{Q_t}{Q_1}\right)^{k_2} \quad (37)$$

For k_1 and k_2 we use the same value of 0.15 as Fischer and Newell (2008), based on the elasticity of R&D in different studies (cf. Nadiri 1993).

We set a constant elasticity R&D investment function, $R(h_1) = \gamma_0 {h_1}^{\gamma_1}$, which has the desired properties as mentioned above as long as γ_1>1.

We also assume a linear demand function $D^{(t)}(P_t) = {d_0}^{(t)} - d_1 P_t$ with time dependent demand level ${d_0}^{(t)}$ and a low price sensitivity d_1 as indicated in Table 1 and shown in Figure 1.

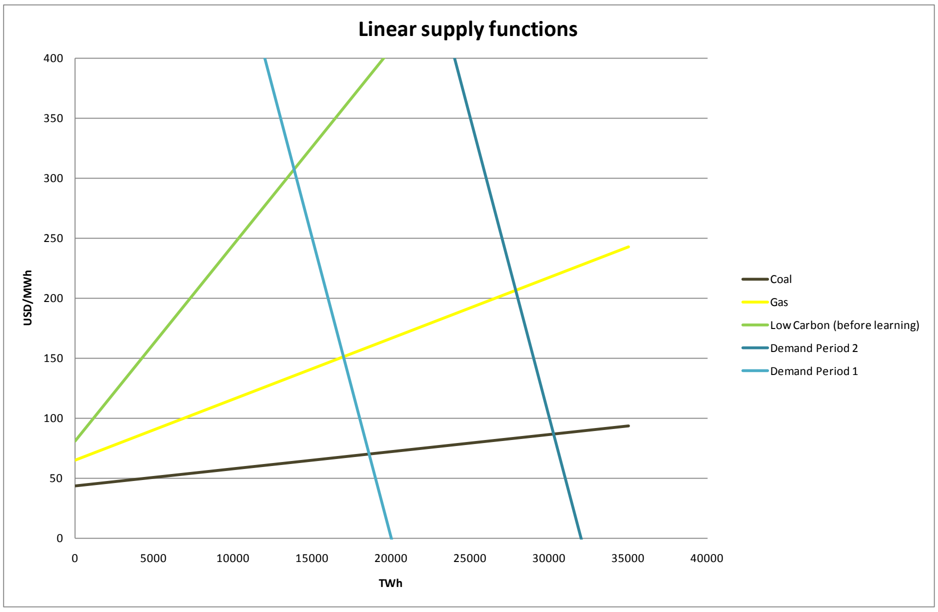

Figure 1: Linear supply functions

For the welfare function (cf. eq. (13)) a logarithmic functional specification is chosen. The firms' utility, i.e. eq (22)and (28) is thereby set to be a linear function of profits, except for the case of bankruptcy, where a 15 % bankruptcy cost is added[4]:

$$S(\pi) = \begin{cases} \pi & \pi \geq 0 \\ 1{,}15\pi & \pi < 0 \end{cases} \tag{38}$$

Also environmental damage is considered to be a quadratic function of emissions with the linear term (marginal environmental damage) being uncertain.

$$B = b_0 - b_1 E - \tfrac{1}{2} b_2 E^2 \tag{39}$$

where $b_1 = \xi$

For the stochastic parameter ξ a uniform distribution between 0 and 100\$/t CO_2 is assumed.

Then B_E corresponds to

$$\begin{aligned} B_E &= -b_1 - b_2 E \\ &= -\xi - b_2 n^{(1)}\left(\mu_x x^{(1)} + \mu_y y^{(1)}\right) \\ &\quad - b_2 n^{(2)} \left(\mu_x x^{(2)}(\xi) + \mu_y y^{(2)}(\xi)\right) \end{aligned} \tag{40}$$

[4] Bankruptcy costs may in general range between roughly 10 to 25 percent of firm value. Cf. e.g. Bris et al. (2006), who analyze the depreciation of book values of 286 companies during their bankruptcy process.

In Table 1 the different parameters and assumptions are summarized. Most of those stem from or are calculated based on data from IEA (2010).

Table 1: Parameters

Parameters					
c_{x0}	0	$\$/MWh_{el}$	$d_0^{(1)}$	20000	TWh/a
c_{x1}	44	$\$/MWh_{el}$	$d_0^{(2)}$	32000	TWh/a
c_{x2}	0.00142985	$\$/MWh_{el}$	d_1	20	TWh/($/MWh)
c_{y0}	0	$\$/MWh_{el}$	b_0	0	Mio. $
c_{y1}	65	$\$/MWh_{el}$	$b_1=\xi$	$\in[0...100]$	$/t
c_{y2}	0.005079	$\$/MWh_{el}$	b_2	0.000001	$/t/Mt
g_0	0	$\$/MWh_{el}$	μ_x	0.9	t/MWh
g_1	81	$\$/MWh_{el}$	μ_y	0.416	t/MWh
g_2	0.01632	$\$/MWh_{el}$	i	10	%
H_1	100000		c_{bankr}	15	%
k_1	0.15		$n^{(1)} = n^{(2)}$	20	a
k_2	0.15		$\delta = e^{-i\,n(2)}$	0.122	
ρ	0.5				
γ_0	1				
γ_1	1.01				

The optimal decision for the second period may then be obtained solving the linear system of equations given in Appendix B: System of equations for second period for a given capital stock K_2 and a given stochastic realisation ξ. When the stochastic distribution is approximated by a discrete distribution, the overall problem may be solved numerically as a non-linear optimization problem with the first-period variables as only unknowns by using the Newton-Raphson-Algorithm. The key results are summarized in Table 2.

Table 2: Key results of the empirical analysis

P_1	104	$/MWh	P_2	113	$/MWh
h_1	88327		$R(h_1)$	98982	Mio. $
q_1	3180	TWh	q_2	10928	TWh
x_1	11085	TWh	x_2	13919	TWh
y_1	3645	TWh	y_2	4897	TWh
E_1	11493	Mt CO_2	E_2	14564	Mt CO_2

With the given data and assumptions, total generation increases by about 65 percent, with conventional production only slightly increasing from approximately 15000 TWh in period 1 (2010-2030) to about 19000 TWh in period 2 (2030-2050). Hence, renewable electricity production increases by a factor of 3.5. Inherently, CO_2 emissions experience a moderate increase of about 25 percent and the electricity price increases by about 10 $/MWh. R&D-investment of 100.000 Mio. $ in the first period are found to be optimal together with an R&D subsidy share of 52%, a clear evidence for a substantial need for R&D support. Production subsidy in contrast seems to be of lower importance as this only accounts for roundabout 1 $/MWh. All in all, a clear rationale for support mechanisms beyond a CO_2-tax or certificate system is given.

Sensitivity analyses indicate that the basic structure of generation and support shares do not change drastically with modified parameters so that optimal policy instruments are rather robust towards the choice of parameters – except for the assumptions on technology spillover.

6 Conclusion

In the presence of massive uncertainties and technology spillovers, well-designed support mechanisms for renewables play a major role, notably as a compensation for technology spillovers, yet also as a means for reducing investors' risks. However, to avoid excessive and unnecessary subsidies, the design of the support mechanisms and therewith the portfolio of instruments needs to be target-aimed and well-focused. Production support mechanisms like feed-in-tariffs provide particularly strong risk reduction to investors, yet a misbegotten scheme may cause excessive burdens to society – as currently experienced for the case of PV support in Germany.

As shown in the theoretical part, three policy instruments are needed for the existing externalities. On the one hand, an emission tax or certificate price, which should equal the marginal environmental damage and an R&D subsidy to compensate for technology spillovers. Under uncertainty, the latter is justified even if knowledge is fully appropriable, under the condition that the firms' risk aversion is higher than societal risk aversion. Furthermore, to compensate the non-appropriable part of learning-by-doing, a production subsidy for low-carbon technologies is needed. Besides the assumptions on technology costs and uncertainty of emission damage cost, technology spillover clearly plays a key role. Yet under some plausible parameter settings, direct subsidies to production are found to be of lower importance than very substantial R&D supports.

All in all, the quantitative results of this study should be considered as an example of modeling for insights rather than for numbers. Yet the theoretical results clearly indicate that the general rules for optimal policy design in the deterministic case also carry through when including uncertainty. However in detail optimal policies may deviate from their deterministic counterparts, at least in the presence of individual risk aversion and imperfect markets for risks.

The model discussed here lends itself to further extensions. Notably uncertainty may be extended to further factors like electricity demand or fuel prices. But also uncertainty within one period may considerably affect the model outcomes.

A further shortcoming of the approach is that no differentiation between manufacturers and producers is included, implying that agency and incentive issues are eliminated from the outset. Furthermore the increasing returns to scale in the case of low carbon energy implies that individual producers may face negative pay-offs, notably if they are not perfectly diversified but are rather owning the marginal unit(s).

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Appendix A: Further welfare FOC's

$$\frac{\partial W}{\partial y^{(1)}} = 0\colon P^{(1)} - C_y'(y^{(1)}) = \frac{\mu_y \int U' \cdot B_E \, d\xi}{\int U' \, d\xi} \tag{41}$$

$$\frac{\partial W}{\partial y^{(2)}} = 0\colon U' \cdot \left(B_E \, n^{(2)} \mu_y + n^{(2)} \left(P^{(2)} - C_y'\left(y^{(2)}\right)\right)\right) = 0 \tag{42}$$

$$\frac{\partial W}{\partial q^{(2)}} = 0\colon U' \cdot \left(P^{(2)} - G_q\left(K^{(2)}, q^{(2)}\right)\right) = 0 \tag{43}$$

$$\frac{\partial W}{\partial s^{(1)}} = 0\colon U' \cdot \left(n^{(1)} q^{(1)} - n^{(1)} q^{(1)}\right) = 0 \tag{44}$$

$$\frac{\partial W}{\partial s^{(2)}} = 0\colon U' \cdot \left(\delta n^{(2)} q^{(2)} - \delta n^{(2)} q^{(2)}\right) = 0 \tag{45}$$

$$\frac{\partial W}{\partial \theta^{(1)}} = 0\colon U' \cdot \left(-n^{(1)}\left(x^{(1)} + y^{(1)}\right) + n^{(1)}\left(x^{(1)} + y^{(1)}\right)\right) = 0 \tag{46}$$

$$\frac{\partial W}{\partial \theta^{(2)}} = 0\colon U' \left(-\delta n^{(2)}\left(x^{(2)} + y^{(2)}\right) + \delta n^{(2)}\left(x^{(2)} + y^{(2)}\right)\right) = 0 \tag{47}$$

$$\frac{\partial W}{\partial \tau^{(1)}} = 0\colon U' \cdot \left(-n^{(1)}\left(\left(\mu_x x^{(1)} + \mu_y y^{(1)}\right)\right) + n^{(1)}\left(\mu_x x^{(1)} + \mu_y y^{(1)}\right)\right) = 0 \tag{48}$$

$$\frac{\partial W}{\partial \tau^{(2)}} = 0\colon U' \cdot \left(-\delta n^{(2)}\left(\left(\mu_x x^{(2)} + \mu_y y^{(2)}\right)\right) + \delta n^{(2)}\left(\mu_x x^{(2)} + \mu_y y^{(2)}\right)\right) = 0 \tag{49}$$

$$\frac{\partial W}{\partial \sigma} = 0\colon U' \cdot \left(n^{(1)} R\left(h^{(1)}\right) - n^{(1)} R\left(h^{(1)}\right)\right) = 0 \tag{50}$$

Appendix B: System of equations for second period

$$\begin{bmatrix} -c_{x2} - {\mu_x}^2 b_2 n^{(2)} & -\mu_x \mu_y b_2 n^{(2)} & 0 & 1 \\ -\mu_x \mu_y b_2 n^{(2)} & -c_{y2} - {\mu_y}^2 b_2 n^{(2)} & 0 & 1 \\ 0 & 0 & -\frac{1}{K^{(2)}} g_2 & 1 \\ 1 & 1 & 1 & d_1 \end{bmatrix} \begin{bmatrix} x^{(2)} \\ y^{(2)} \\ q^{(2)} \\ P^{(2)} \end{bmatrix} = \begin{bmatrix} c_{x1} + \mu_x\left(\xi + b_2 n^{(1)} E_1\right) \\ c_{y1} + \mu_y\left(\xi + b_2 n^{(1)} E_1\right) \\ \frac{1}{K^{(2)}} g_1 \\ d_0 \end{bmatrix} \tag{51}$$